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13. ABSTRACT (Maximum 200 words) The objective of this research was to improve understanding of the mechanisms by which flow, mixing and combustion processes are coupled to acoustic fields in liquid-propellant rocket motors. Particular attention was focused on analyses of amplification mechanisms coupled with finite-rate chemical reactions by use of numerical and analytical methods. Special attention was focused on LOX/GH ₂ systems and suggested a possible explanation of threshold phenomena found in liquid-propellant rockets. Reduced chemistry was developed for describing LOX combustion in GH ₂ , and approaches towards explaining droplet burning-time minima in the transcritical regime were completed. The results can be helpful in improving knowledge of combustion mechanisms and combustion instability in liquid-propellant rocket motors at high pressures.					
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FINAL REPORT

**FUNDAMENTALS OF ACOUSTIC INSTABILITIES IN LIQUID PROPELLANT ROCKETS
UNDER TRANSCRITICAL CONDITIONS**

(AFOSR Grant No. F49620-97-1-0098)

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INTRODUCTION

Acoustic instability in liquid-propellant rocket engines employing hydrogen and oxygen as propellants at high pressures is of concern in newly evolving concepts of propulsion systems. Results were obtained on research addressing mechanisms of amplification of acoustic waves by the combustion processes in such systems. Consideration was given to influences of chemical-kinetic mechanisms, both detailed and reduced, on the acoustic response. It was found that a four-step approximation for the chemistry can give good agreement with full chemistry. Various physical mechanisms that occur in the vicinity of the critical point for burning droplets of liquid oxygen in gaseous hydrogen atmospheres were identified from the standpoint of their potential influences on the amplification of acoustic oscillations. The results improve knowledge of processes that may affect combustion instability under transcritical conditions. The following sections describe these results in greater detail.

ACCOMPLISHMENTS

It is convenient to summarize accomplishments in specific categories.

1. Rotational Inviscid Flow Effects In Laterally Burning Motors

As a first step towards investigating instabilities, steady-state flow fields in rocket motors were addressed [1]. A theoretical analysis to determine the effects of mass addition on the inviscid but rotational and compressible flowfield in a porous duct with the injection rate dependent of the local pressure was performed for large ratios of length to duct diameter. The problem of describing the flow was reduced to the solution of a single integral equation. The ratio of specific heats, γ , and a constant pressure exponent, n , measuring the dependence of the rate of mass injection on the local pressure, are the parameters of the solutions. The integral equation was solved numerically, and parametric results were obtained for γ varying from 1 to $\frac{5}{3}$ and for n varying from 0 to 1. A choking phenomenon is exhibited at a critical length of the duct in the vicinity of which the Mach number approaches unity. The choking condition, which is relevant to operation of nozzleless solid-propellant rocket motors, was obtained parametrically and compared with corresponding results for irrotational, quasi-one-dimensional flow. The

rotationality reduces the choking pressure. The results are especially useful for describing flow fields in solid-propellant rocket motors.

2. Effects of Spatial and Temporal Inhomogeneities Produced by Turbulence and by Two-Phase Flow

Two distinct approaches to the theory of stochastic effects in the combustion instability of liquid-propellant rockets were developed. In one approach [2], dealing with effects of spatial inhomogeneities in the acoustic medium associated with two-phase flow and with turbulence, attention is restricted to the particular class of interactions in which the characteristic time scale of turbulence is asymptotically large compared with that of acoustic waves, so that the acoustic medium is considered to be a quasistationary random medium. In addition, it is assumed that the acoustic wavelength is long compared with any scale of inhomogeneity within the chamber, motivating a homogenized description, in which averages of state variable becomes appropriate. On the basis of these assumptions, the Navier-Stokes equations for two-phase flows were reduced to a nonhomogeneous stochastic Helmholtz equation. Source terms of the equation were identified as arising mainly from phase change, from homogeneous chemical reaction, and from spatial variations of wave properties such as sound speed.

To handle the stochastic wave equation, the method of smooth perturbation was used and resulted in a Helmholtz equation for an equivalent deterministic acoustic medium. With use made of Green's integral theorem, the dispersion relation for transverse acoustic modes in cylindrical chambers was obtained in the form $k^2 = k_0^2 + ik_0^2 a + k_0 b \cdot k + k_0^4 c$, where a , b and c are calculated from appropriate averages of source terms. In particular, the $k_0^4 c$ term corresponds to the stochastic contributions arising mainly from the spatial correlations of the sound speed with the pressure response function, and of the local Mach number with the velocity response function. Compared with the deterministic contributions to the linear growth (or damping) rate, the stochastic contributions are found to be of the order of $(\ell_t / R)^{3/2}$ where ℓ_t is the characteristic length scale for turbulence and R is the chamber diameter, thus implying that most of the stochastic contributions comes from the larger turbulent eddies. The stochastic effects are expected to be significant in the transition regime in which the deterministic growth rate is close enough to zero for transition between stable and unstable domains to occur reasonably frequently by stochastic variations of the growth rate.

In another approach [3], emphasizing influences of turbulent-induced noise, the behavior of high-frequency combustion instabilities influenced by random temporal variation of the linear growth rate in this same transition regime are addressed. The Raleigh criterion was generalized to account for turbulence-related spatial variations of the combustion response. Special attention was given to the distinguished limit in which the acoustic oscillations are rapid compared with the turbulent fluctuations, which in turn are rapid compare with the linear growth rate of the instability. It was shown that nonlinear acoustics of the instabilities need to be considered to describe the influences of turbulence. When this nonlinearity involves supercritical bifurcation, the turbulence tends to decrease the most probable intensity of the instability. When it involves subcritical bifurcation, the turbulence can produce a bimodal probability density function for the intensity of the instability, with appreciable probabilities of high-amplitude and low-amplitude

acoustic oscillations but small probabilities of oscillations of intermediate amplitudes. These phenomena can have a bearing on erratic pressure-amplitude bursts sometimes observed in liquid-propellant engines.

A key observation of this last study is that the turbulence influences on the acoustics appear as multiplicative rather than additive noise. Comparison of the turbulence coherence time with the characteristic time of the combustion instabilities identifies two distinct interaction classes, depending on whether the coherence time is or is not much smaller than the characteristic instability growth time. Larger instabilities are associated with the second of these classes while the transition behavior in the first class involves random walks of the stochastic linear growth rate, requiring a statistical description. In a white-noise approximation, the Stratonovich rather than Ito interpretation of the stochastic integral must be employed, and the Markov property of the white-noise process then enables the evolution of the probability density of the pressure amplitude to be described by Fokker-Planck equation, whose stationary solutions lead to transition behavior that depends on the character of the bifurcation. There is a bimodal behavior for subcritical bifurcation in the hysteresis region. The size of the bimodal transition region is proportional to the time integral of the autocorrelation function of the turbulence-induced fluctuations of the linear growth rate. This result provides a possible mechanism for resurging patterns of the pressure amplitude.

3. Amplification Mechanisms Coupled with Finite-Rate Chemistry

Many different processes can contribute to linear amplification of acoustic oscillations in liquid-propellant rockets, and asymptotic analyses of these processes can help in assessing combustion instabilities. One such process is the strained planar diffusion flame. Previous studies of diffusion-flame response postulated infinite chemical reaction rates (the Burke-Schumann approximation). On the contrary, the work on this project [4] took into account the influences of finite-rate chemistry, which can become important in environments having high turbulence intensities. The results demonstrate that the high sensitivity of the chemical reaction rates to temperature fluctuations can underlie important amplification mechanisms. As an initial simplification, a one-step, irreversible Arrhenius-type chemical reaction rate was employed, and a gaseous counterflow diffusion flame was adopted to represent flamelets subjected to nonuniform flow fields caused by turbulent fluctuations. It is intended later to introduce rate-ratio asymptotics for hydrogen-oxygen systems [5,6].

The analysis was performed by activation-energy asymptotics. The resulting flame structure for a given value of the reaction-sheet location is described by two sets of equations, one for the transport of momentum, thermal energy and reactant, and the other for the corresponding overall reaction rate of the flame. The acoustic response of the flame, obtained from the linear analysis, is found to be determined by two mechanisms [4], namely, oscillations of the reaction sheet induced by acoustic-produced fluctuations of the reaction rate, and oscillations of the field variables produced by the transport-zone response. The results show that analyses for the acoustic response of flames that do not consider finite reaction rates could significantly underestimate the amplification rate. That is, the first of the two mechanisms, which was not considered in previous studies, can provide the major amplification.

This analysis of pressure response was extended to consider velocity response [7]. The response of counterflow flames to oscillating strain rates was analyzed by using activation-energy asymptotics, as a further potential application to turbulent combustion and acoustic instability of rocket engines. The characteristic oscillation time of practical interest is found to be of the same order as the characteristic diffusion time of the flame, so that the flame structure consists of a quasi-steady reactive-diffusive layer embedded in the outer unsteady diffusive-convective zone, as before [4]. A linear analysis was conducted by assuming that the amplitude of the strain-rate oscillation is small relative to the mean strain rate. Results showed that the flame response is controlled mainly by two effects: (a) the response of the convective mass flux into the reaction sheet, which is directly related to the flow-field variation applied at the boundary, and (b) the response of the reaction sheet to adjust the reduced residence time to the finite-rate chemistry, as before [4]. For flames near equilibrium, the former effect tends to be dominant, so that the response of the net heat release is in phase with the strain-rate oscillation. For flames near extinction, however, the finite-rate chemistry effect overtakes the fluid-dynamic effect, such that increasing strain rate leads to a reduction of the reactivity of the flame during the oscillatory cycle. As such, the net heat-release response of the near-extinction flame becomes out of phase with the strain rate oscillation in the sense of the Rayleigh's criterion. Results thus suggest the possibility that the unsteady velocity-response characteristics of the near-extinction diffusion flame can be significantly different from those in the Burke-Schumann limit and also from those for the pressure response, which often is strongly destabilizing.

As another model for the combustion response, consideration was given to acoustic pressure response of spherical droplet flames in the premixed-flame regime of activation-energy asymptotics, to examine acoustic instability mechanisms in liquid-propellant rocket engines [8]. Depending on the diameters of the droplets, the combustion condition is classified as near-equilibrium or near-extinction, and the acoustic pressure response for each condition was determined for a wide range of the acoustic frequency. Compared with the results previously obtained for strained diffusion flames, the reaction sheet of the droplet flame is found to exhibit a behavior similar to that of strained diffusion flames, in that the reaction sheet moves toward the oxidizer boundary, at which the mass flux of the oxidizer is greater, to balance the high reactivity during the period of high acoustic pressure. Oscillations of the reaction sheet, however, give rise to an additional attenuation mechanism, associated with reduction of the reaction-surface area, thereby resulting in a much smaller response of the heat-release rate for droplet flames than that for strained diffusion flames. This initially surprising finding redirected attention to the finite-rate chemistry effect in the pressure response of the strained diffusion flames as the major mechanism driving acoustic instability in liquid-propellant rocket motors.

A test of this conclusion was made by considering the empirical Hewitt stability correlation for liquid-propellant rocket engines employing LOX/RP-1 propellant combinations with like-on-like impinging-jet injectors [9]. Empirically, there is a critical value of the frequency ω times the ratio of the injector orifice diameter d to the injection velocity u below which acoustic instability occurs. The instability will develop when the amplification rate through the combustion response exceeds the attenuation rate through the sum of the different damping mechanisms. The amplification rate by strained diffusion flames exhibits a marked increase with decreasing ω at a critical value of the nondimensional frequency ω/a , where a denotes the strain rate of the diffusion flame [4]. This increased amplification rate can overcome

the total damping rate and thereby lead to instability. The appropriate value of a in this application is an average strain rate for the diffusion flamelets in the turbulent reacting flow between the fuel and oxidizer fans. This average, however, is proportional to u/d over a substantial region in the vicinity of the injector face, where the dominant amplification occurs. The observed critical value of $\omega d/u$ for instability thus is consistent with prediction.

4. Effects of Distributed Combustion-Chamber Nonhomogeneities

As a further advance in abilities to describe acoustic instabilities in rocket chambers with improved accuracies, an analysis was completed determining mode shapes in nonhomogeneous chambers. Modifications to acoustic eigenmodes in combustion chambers such as those of liquid propellant rocket engines, produced by spatial variations of density and sound speed that arise mainly through progress of combustion processes, were analyzed by using a variational method. The variational principle shows that the eigenvalue is the ratio of a weighted acoustic kinetic energy to a weighted acoustic potential energy, and the eigenfunction is the minimizing function of this ratio. A sample calculation was made for the case in which variations of the properties occur dominantly in the longitudinal direction, with lower temperatures and higher densities prevailing near the injector. The results of the calculation exhibit two major characteristics: the longitudinal density variation aids transfer of acoustic kinetic energy from a lower mode to the adjacent higher mode, so that the pure transverse modes have substantially larger reductions (sometimes exceeding 50%) of their eigenvalues than the combined modes; also variations of the acoustic pressure gradients were found to be larger in high-density regions, so that the acoustic pressure amplitude for purely tangential modes is much higher near the injector than near the nozzle. The higher head acoustic pressure may contribute to the greater sensitivity of acoustic instability to characteristics of the flames near the injectors, as commonly found in engine tests. The improved acoustic eigensolutions can also be helpful in sizing damping devices, such as baffles or acoustic liners.

5. High-Pressure Acoustic Instability in Hydrogen-Oxygen Liquid-Propellant Rockets

In further work, acoustic instability in liquid-propellant rocket engines employing hydrogen and oxygen as propellants at high pressures was investigated because of concern in newly evolving concepts of propulsion systems[11]. Results were obtained on mechanisms of amplification of acoustic waves by the combustion processes in such systems. Consideration was given to influences of chemical-kinetic mechanisms, both detailed and reduced, on the acoustic response. It was found that a four-step approximation for the chemistry can give good agreement with full chemistry. Various physical mechanisms that occur in the vicinity of the critical point for burning droplets of liquid oxygen in gaseous hydrogen atmospheres were evaluated from the standpoint of their potential influences on the amplification of acoustic oscillations. The results improved knowledge of processes that may affect combustion instability under transcritical conditions.

In particular, the flame structures and extinction characteristics of undiluted hydrogen-oxygen strained diffusion flames at high pressures were studied numerically with detailed and reduced chemistry for the intended purpose of application to acoustic instabilities of rocket engines [12]. The numerical extinction results for undiluted hydrogen-oxygen flames were

found to be qualitatively different from those for hydrogen-air flames in that extinction strain rates for undiluted hydrogen-oxygen flames increase linearly with pressure up to 100 atm but extinction strain rates for hydrogen-air flames bend over and reach a maximum around 50 atm. Comparison of the characteristic flow time with the characteristic chemical time shows that extinction strain rates vary linearly with pressure for flames controlled by two-body chain-branching reactions, and therefore the results suggest that these reactions are dominant in real motors. Four-, three, and two-step reduced mechanisms also were tested and showed that the linearity of the extinction strain rate with pressure is preserved. Based on these results, the asymptotic methods previously used in low-pressure hydrogen-air flames can be extended to predict the asymptotic structure of hydrogen-oxygen flames at high pressures. Fall-off real-gas effects were found to have minimal influences on extinction characteristics. Since the characteristic flow time is estimated to be several orders of magnitude shorter than the characteristic acoustic time in rocket engines, acoustic responses are satisfactorily reproduced from the quasisteady flame structures. It was found that the reaction step $H + O_2 + M \rightarrow HO_2 + M$ exerts a favorable influence tending to stabilize acoustic oscillations by depressing the reaction rate.

6. Effects of Multicomponent Hydrocarbon Fuels on Liquid-Propellant Rocket Combustion

For motors employing RP-type fuels, there are uncertainties about influences on combustion of the fact that these fuels are not pure hydrocarbons but instead are mixtures. To improve understanding of these multicomponent-fuel effects, binary mixtures were studied at high pressures, with special emphasis on n-heptane, n-hexadecane mixtures as an example [13]. For most mixtures the total burning time was observed to achieve a minimum value at pressures well above the critical pressure of either of the pure fuels. This behavior was explained in terms of critical mixing conditions of a ternary system consisting of the two fuels and nitrogen. The importance of inert-gas dissolution in the liquid fuel near the critical point was thereby emphasized, and nonmonotonic dependence of dissolution on initial fuel composition also was demonstrated. The results provide information that can be used to estimate high-pressure burning rates of fuel mixtures of interest in rocket propulsion.

7. Intrinsic Instabilities of Diffusion Flames

In related work that did not concern acoustic interactions, intrinsic instabilities and extinction of diffusion flames were studied by methods of activation-energy asymptotics [14,15]. These instabilities can be relevant to instabilities found in liquid-fueled motors. Unlike premixed systems, intrinsic instabilities of combustion are less prevalent in nonpremixed systems and are much more difficult to analyze by asymptotic methods. A successful instability analysis was completed, exhibiting good agreement with experiment [14]. This analysis did not address detailed or reduced chemistry, the potential influences of which need study. There is reason to believe, however, that the results of the analysis are qualitatively quite realistic.

8. Theory of Transcritical Droplet Combustion

Since transcritical conditions often can occur in liquid-propellant rocket motors, an approach to the theory of droplet combustion at criticality was developed [16]. Specifically, the

heating of a cold fluid packet, introduced at critical conditions into a hotter environment of the same fluid at the critical pressure, was analyzed. Critical anomalies of the fluid transport properties, as well as a general equation of state, were taken into account. For times longer than the characteristic acoustic time, the heat transfer becomes a convective-diffusive isobaric transient process. An asymptotic theory valid in the limit of a small ratio between the fluid densities in the hot and cold regions was developed. The divergence of the thermal conductivity at the critical temperature controls the heat transfer to the cold region according to the results of this theory. There exists a well-defined boundary, denoted by $R(t)$, dividing two distinguishable regions. The outer region extends from the far field to $R(t)$, where the critical temperature T_c is reached. There, the temperature gradient vanishes as a consequence of the divergence of the thermal conductivity. Heat therefore does not penetrate into the inner cold region, where the temperature remains equal to T_c . The heating of the initially cold fluid takes place instead by recession of the boundary $R(t)$. There is a temperature profile in the outer region which is quasisteady in a reference system receding with $R(t)$, and $R^2(t)$ decreases linearly with time. The recession velocity and thus the vaporization time are thereby obtained as functions of the geometry and of the far-field conditions. Extensions of this theory could be quite useful for describing transcritical combustion in liquid-propellant rocket motors.

CONCLUSIONS

A number of different problems have been addressed relevant to transcritical combustion and combustion instability in rocket motors. This research resulted in publications, listed in the next section, where the necessary details can be found. By improving understanding of transcritical processes and instability, this work developed information that can be used to help to improve rocket-motor performance and reliability.

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